



# Other Searches in ATLAS and CMS

Rachid Mazini

*Institute of Physics, Academia Sinica Taiwan*

On behalf of the ATLAS and CMS Collaborations



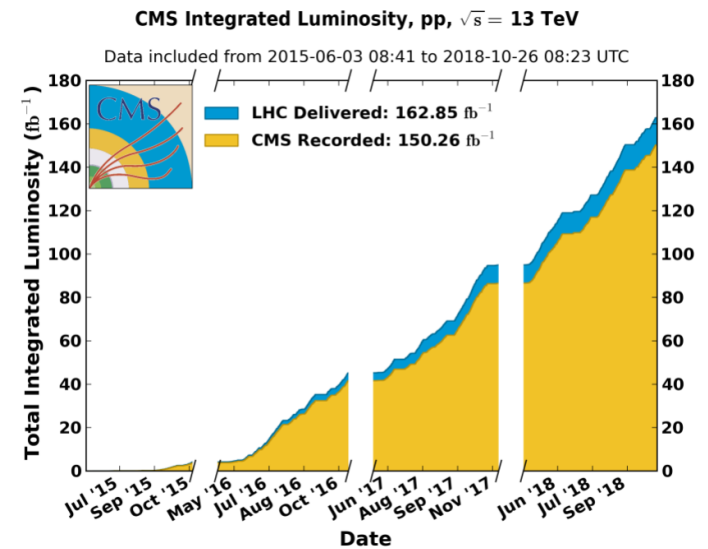
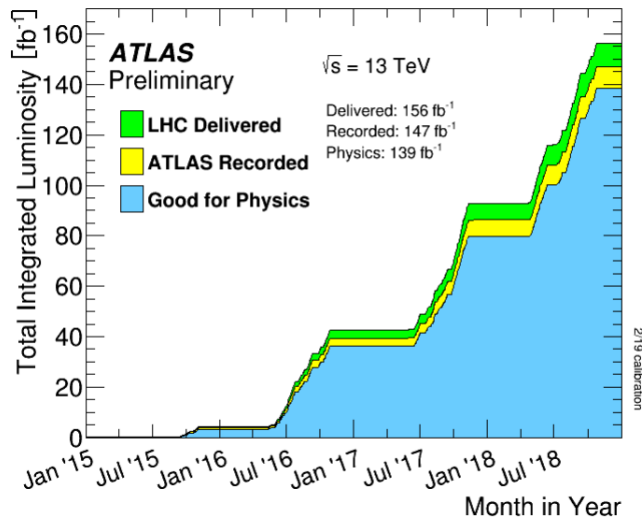
**The XXVIII International Conference on  
Supersymmetry and Unification of  
Fundamental Interactions (SUSY 2021)**

# Introduction

- LHC Run 2 is goldmine for HEP studies.
  - Large dataset with well understood detector performance
  - Multiple new techniques for background estimation, signal enhancement..
    - Improved boosted object tagging, high performance Machine/Deep learning approaches...
- Run 2 analyses are still in full production mode
  - Both ATLAS and CMS continues to provide high precision measurements for SM processes. Determine fundamental parameters, probe higher-order QCD and EW effects
    - Most results goes well beyond the standards set by LEP/Tevatron
  - Access to rare, poorly understood processes to investigate untested SM sectors
- Broad search program at TeV scale and beyond (high energy frontier) and (ultra?) weak interactions
  - Help to address fundamental questions in SM description
    - Naturalness, dark matter, flavor puzzles, etc

# Run 2 data

- ATLAS and CMS have collected an impressive amount of high quality data from pp collisions at  $\sqrt{s} = 13$  TeV, in addition to the heavy ions collision program



- Only a subset of results are presented here, mostly recent ones in non-Higgs/SUSY/DM searches
- Full list can be found here:
  - ATLAS: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018>
  - CMS: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/CMS/index.html>

# Searches for Diboson resonances

Many models predict some kind of diboson resonances:

Extra-dimensions

Warped ED, spin-0 Radion, Graviton

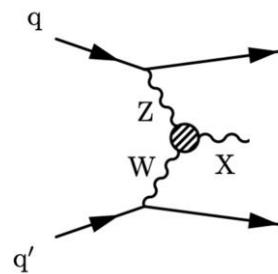
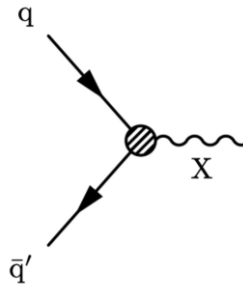
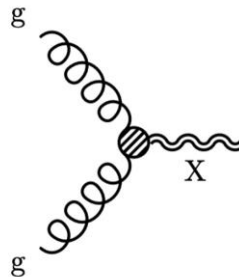
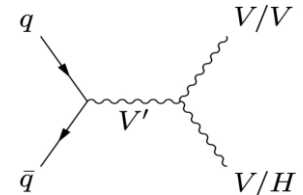
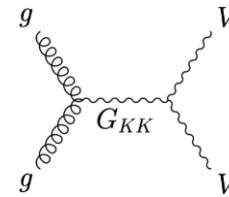
Heavy vector triplet (HVT)

Spin-1  $W'$ ,  $Z'$  coupling to SM

Little Higgs model, Two Higgs doublets models, Technicolor

3 productions modes, for new heavy bosons at TeV scale

ggF, DY, VBF

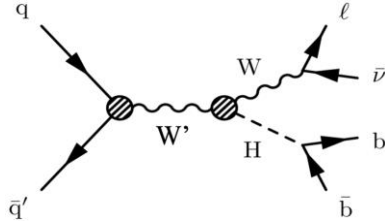


Decay mode includes  $VV$ ,  $VH$ :

See [William Balunas'](#) talk for an extensive review.

# Searches for Diboson resonances: $W' \rightarrow WH \rightarrow l\nu bb$

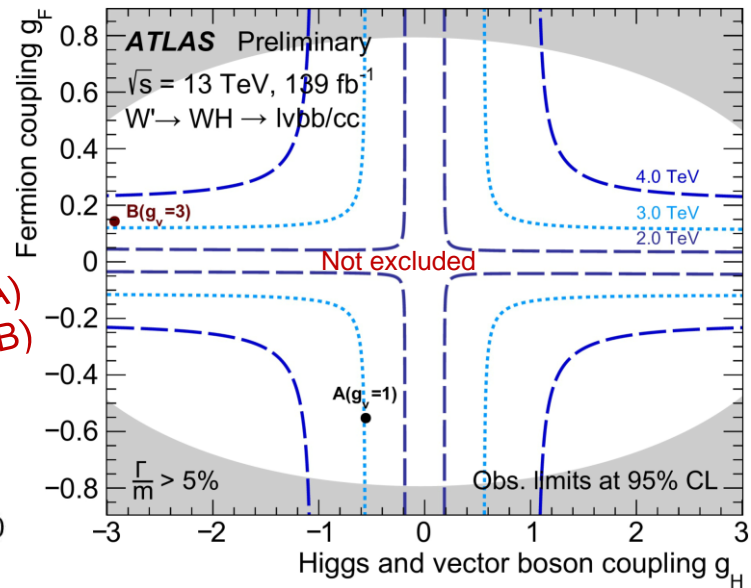
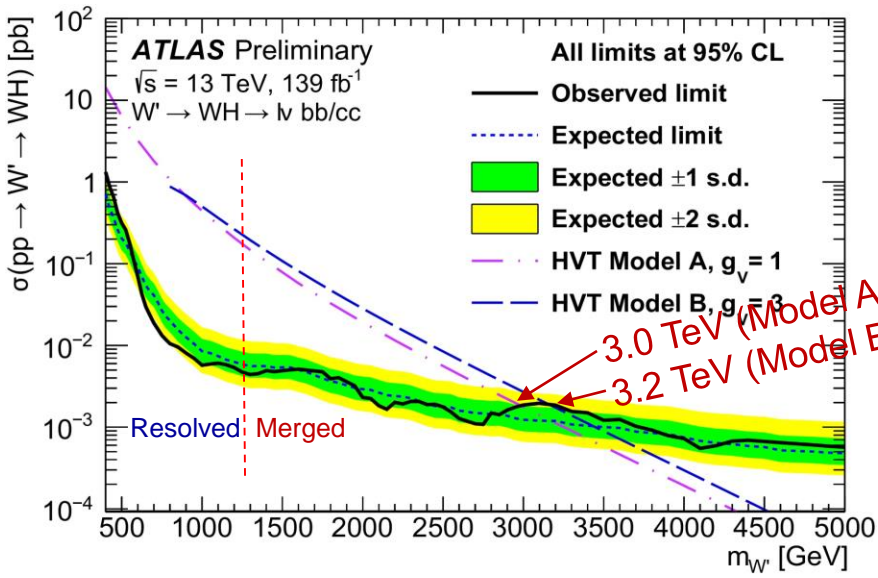
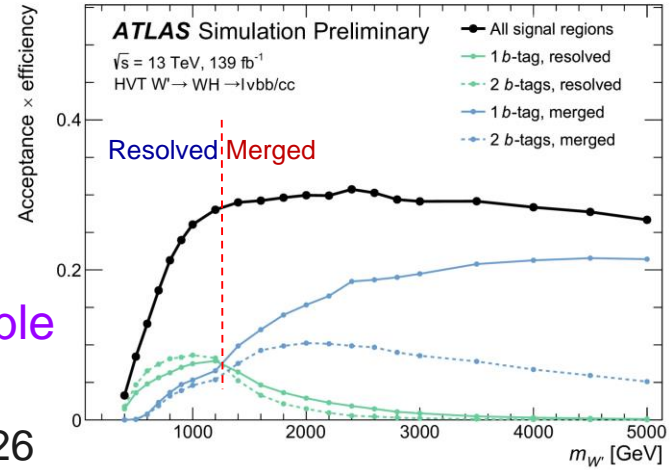
- Analysis uses merged/resolved H boson decay to categorize events in addition 1,2 b-tagged jets



- Use  $M_W$  constraint and  $M_{WH}$  observable
- Main background

Top, W+hf, W+l

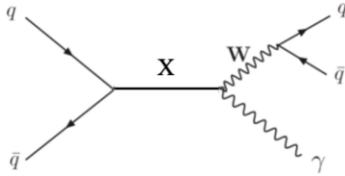
CONF-2021-026



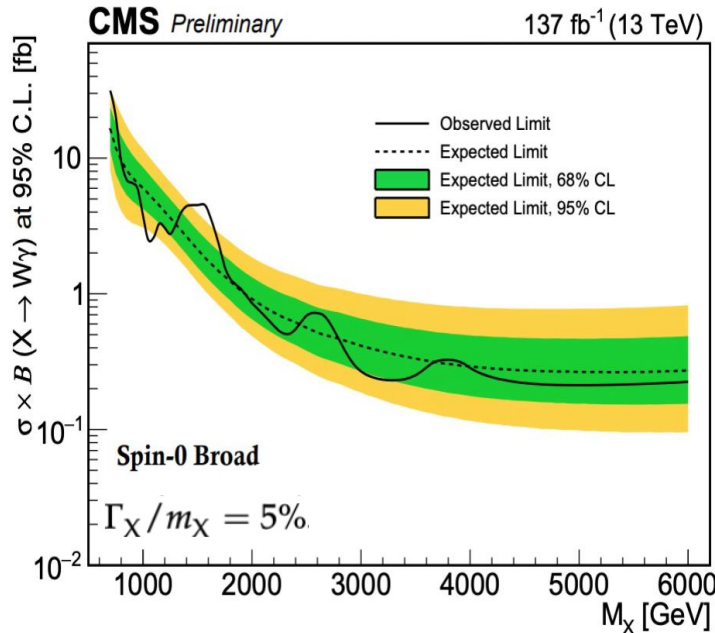
# Other Diboson searches

$$X \rightarrow W\gamma \rightarrow qq \gamma \quad (\text{EXO-20-001})$$

- Generic searches with merged (W) qq and central  $\gamma$



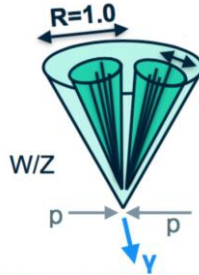
- Limits on  $\sigma_{pp} \rightarrow X \times \text{Br}(X \rightarrow Wqq\gamma)$ 
  - 3.1(2.8) $\sigma$  broad(narrow) at  $M_X \sim 1.6\text{TeV}$
  - 1.7(1.1) $\sigma$  global



$$X \rightarrow V\gamma \quad (\text{CONF-2021-041})$$

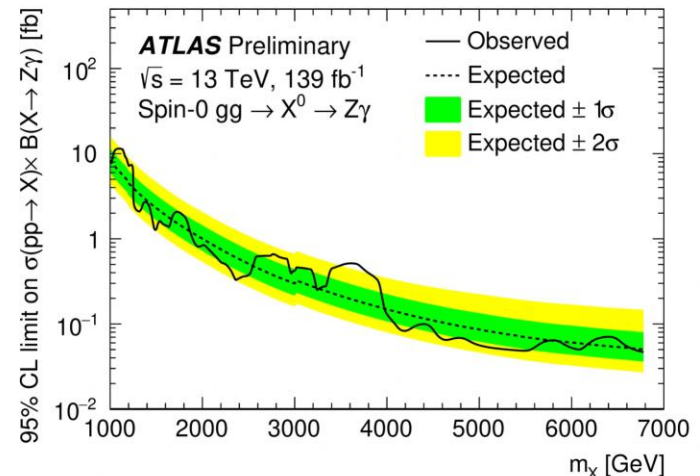
- New results, focus on merged W/Z

- Boosted hadronic W/Z decay
- Events split into orthogonal signal regions (W, Z)
- Unbinned likelihood fit of a parametric function to data in each region



- No significant discrepancy from SM

- Set limits on  $\sigma$  over a wide mass range
- Spin-0, 1 and 2 models
- Similar limits on  $W\gamma$



# Tri-Bosons searches: $X \rightarrow RW \rightarrow WWWW$



## First WWW resonances searches

B2G-20-001, B2G-21-002

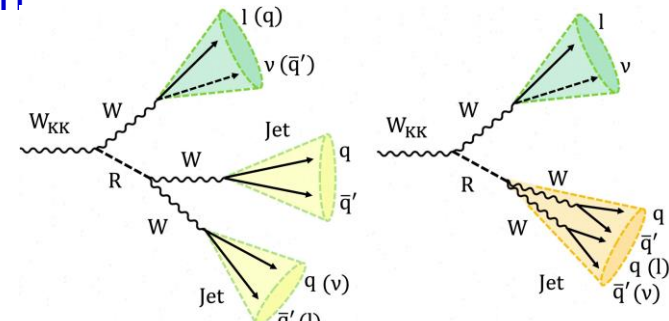
- Extended Wrapped ED (arXiv:1711.09920). Enhanced tri-boson
- Only EW in extended bulk dominant:  $V_{KK} \rightarrow R V \rightarrow VVV$

## Probe simultaneously merged and resolved Radion

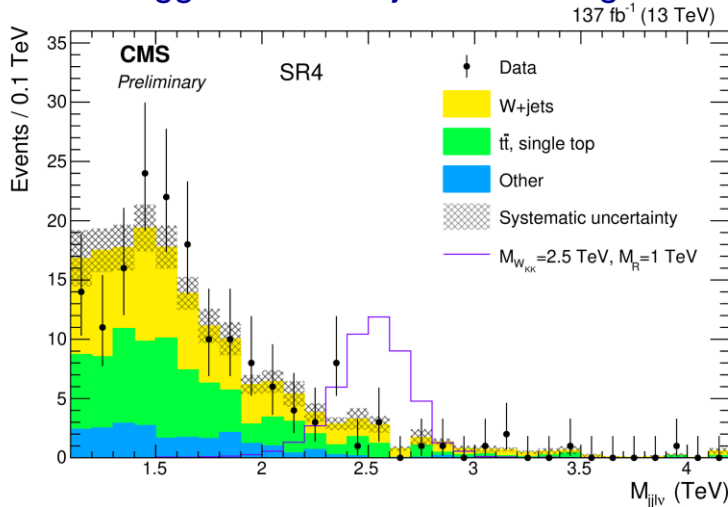
- H4q and Wqq for Wand R taggers

Resolved Radion

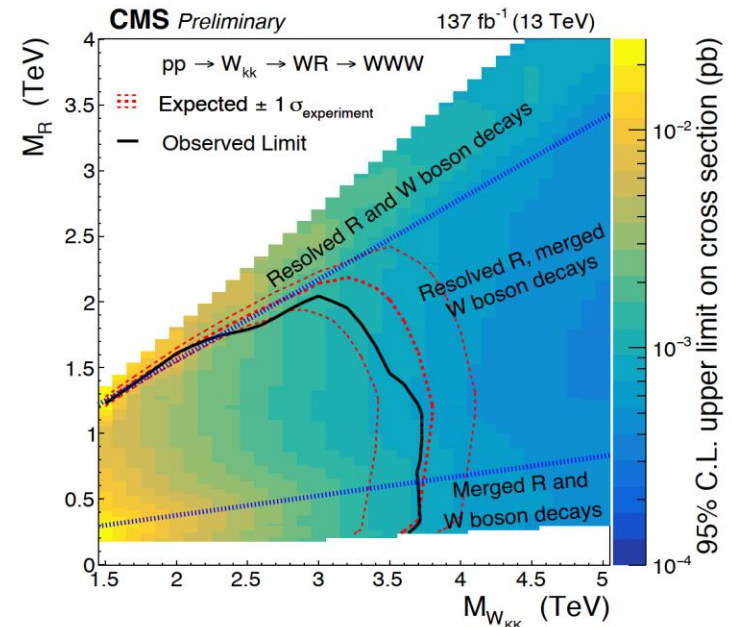
Merged Radion



## 2 W-tagged massive jets + Wlv region

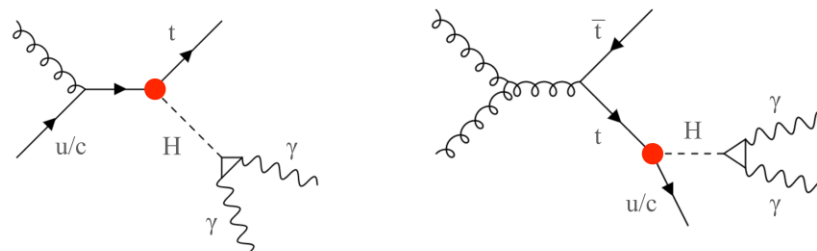


- First limits on  $\sigma(W_{KK} \rightarrow RW \rightarrow WWWW)$  and on  $[M_{WKK}, M_R]$  space with combination of semi-leptonic hadronic final states



# Search for FCNC in the top quark sector

- Flavor changing neutral currents (FCNC) allow for transitions between quarks of different flavor but same electric charge
  - FCNC processes are highly suppressed in the SM due to the GIM mechanism, with small contributions appear at one loop level
- ATLAS and CMS explored FCNC in the top sector via  $tHq$  process ( $q=u,c$ )
  - Using several H decay modes:  $\gamma\gamma$  (CMS),  $bb$  (ATLAS+CMS),  $\tau\tau$  (ATLAS)



- Dominant background: resonant (resonant:  $ttH$ ,  $VH$ ,  $VBF$ ,  $ggH$ ,  $bbH$ ,  $tH$ ), non-resonant ( $tt$ ,  $V+x$ ,  $QCD$ ...)
- Signal regions: categorized for maximum signal sensitivity ( $N_{jets}$ ,  $N_{bjets}$ ,...)
- Several strategies for signal-to-background separation
  - BDT-based or Likelihood-based discriminant



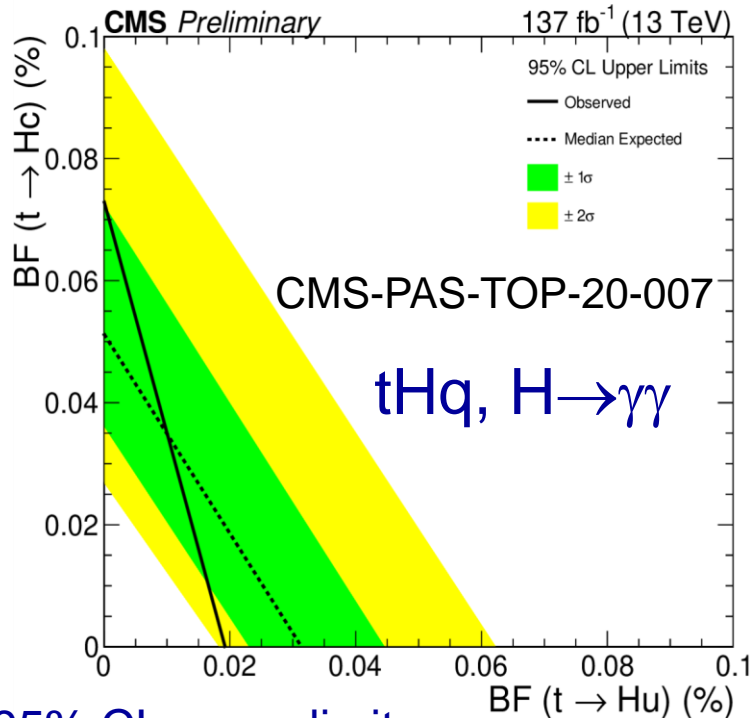
# Search for FCNC in the top quark sector



- Signal modeling: effective Lagrangian

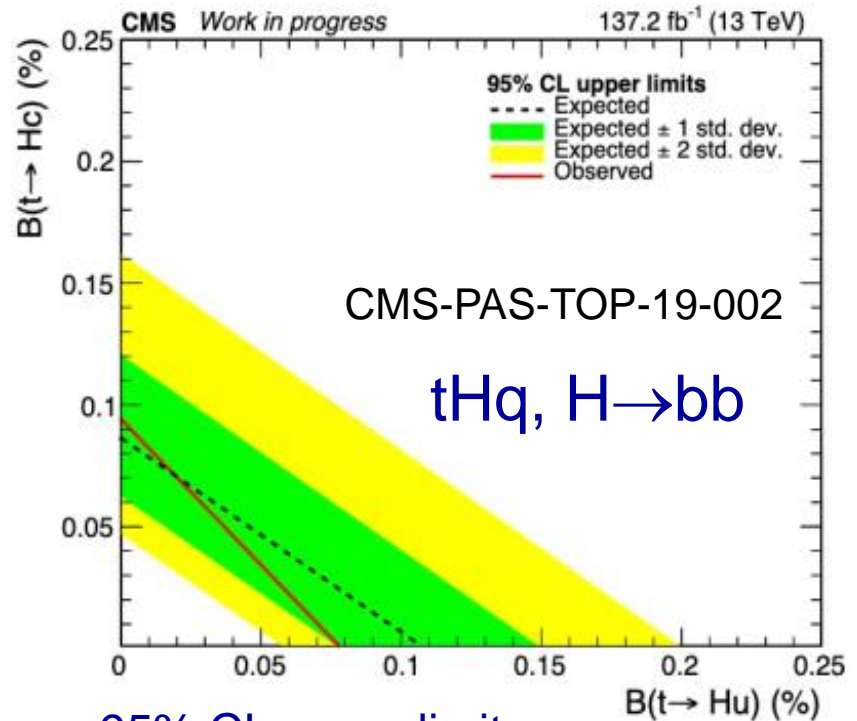
$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} \left( F_{Hq}^L P_L + F_{Hq}^R P_R \right) q H + \text{h.c.},$$

- Upper limits on the signal cross sections are translated to the strength of the tqH anomalous couplings and related branching fractions



95% CL upper limits:

- $B(t \rightarrow Hu) < 1.9 \times 10^{-4}$  (exp.  $3.1 \times 10^{-4}$ )
- $B(t \rightarrow Hc) < 7.3 \times 10^{-4}$  (exp.  $5.1 \times 10^{-4}$ )



95% CL upper limits:

- $B(t \rightarrow Hu) < 8 \times 10^{-4}$  (exp.  $11 \times 10^{-4}$ )
- $B(t \rightarrow Hc) < 9 \times 10^{-4}$  (exp.  $9 \times 10^{-4}$ )

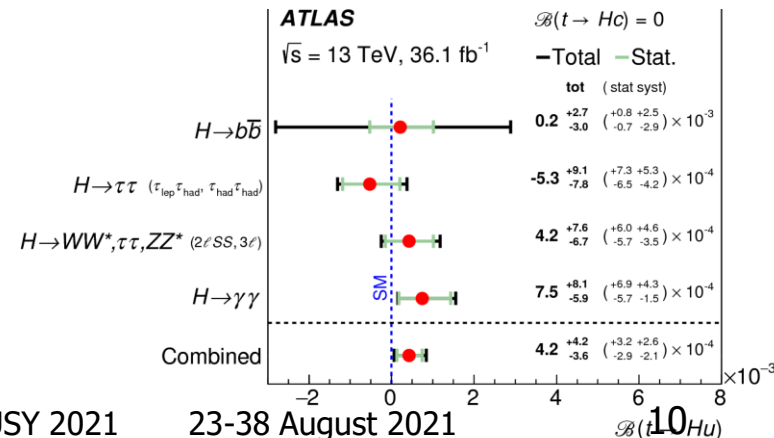
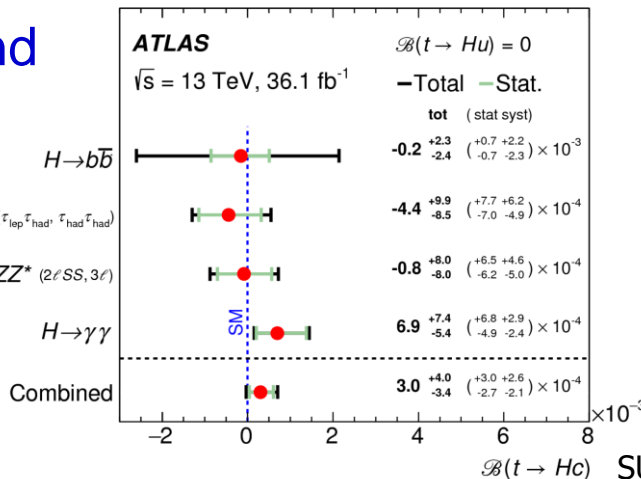
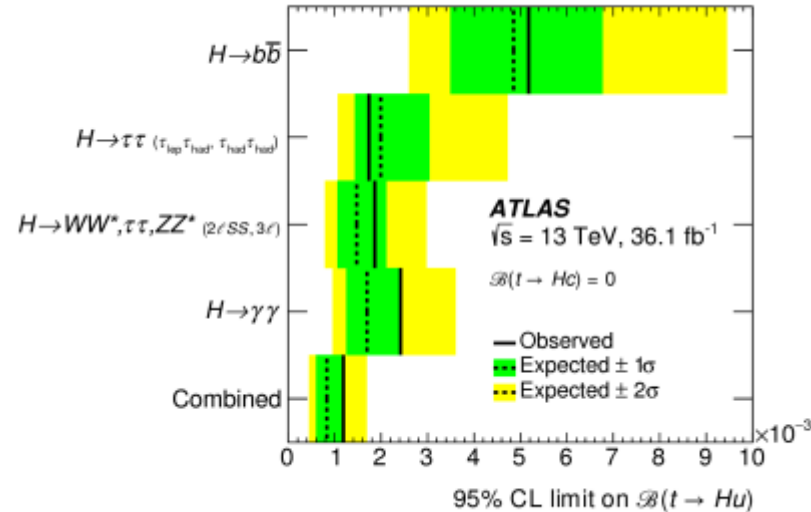
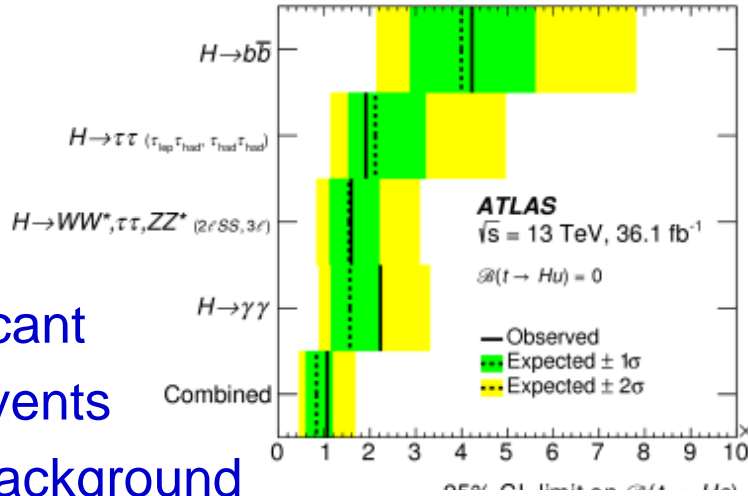
# Search for FCNC in the top quark sector

Searches for  $tHq$  ( $q = u, c$ ) FCNC decays in  $t\bar{t}$  events ( $36 \text{ fb}^{-1}$ ) JHEP 05 (2019)

- $H \rightarrow b\bar{b}$  and  $H \rightarrow \tau\tau$  final states
- Results are combined with  $H \rightarrow \gamma\gamma$  (JHEP10 (2017) 129) and  $H \rightarrow WW^*, \tau\tau, ZZ^*$  ( $2l\nu SS, 3l$ ) (Phys. Rev. D 98, 032002)

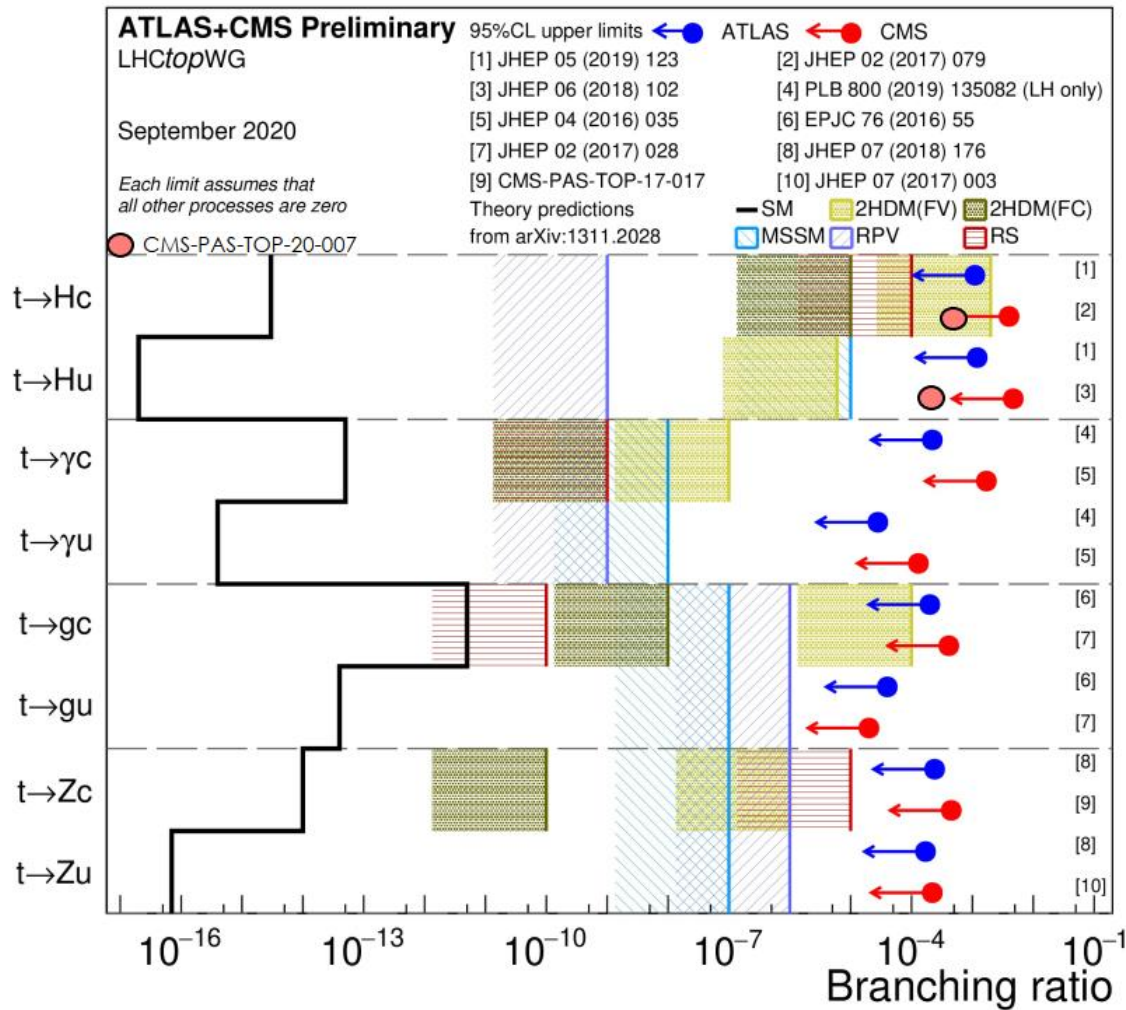


No significant excess of events above the background expectation is found



# Summary of FCNC searches

- Various channels were used to probe FCNC signatures in the top sector
- Achieved precision allows to start probing models with highest BRs.

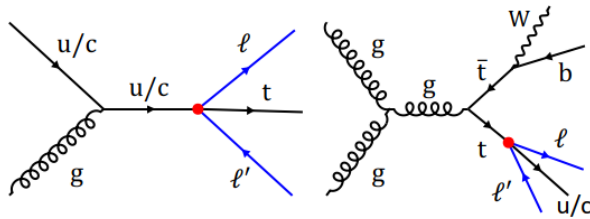




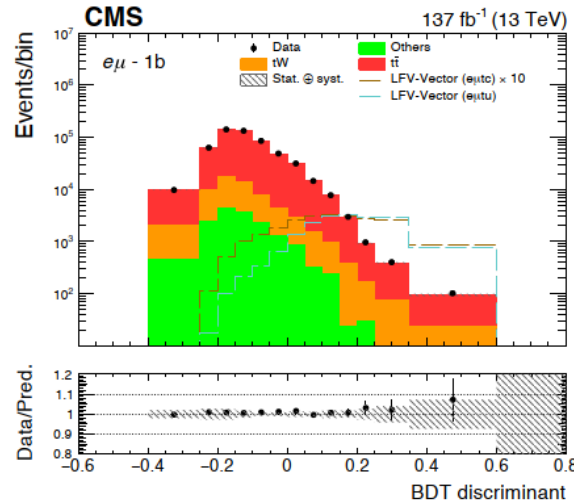
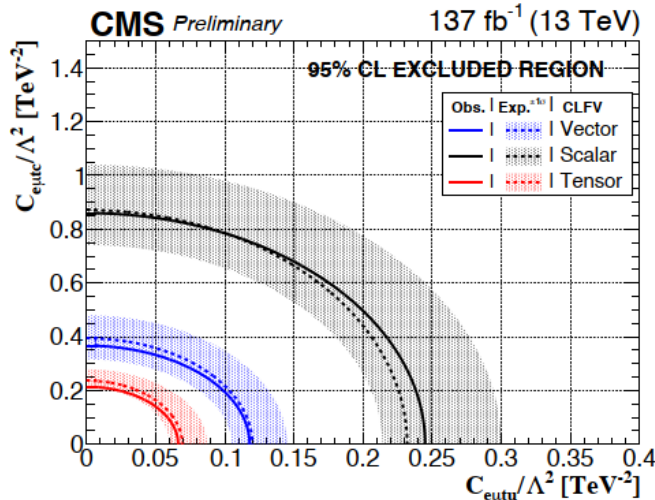
- Using  $t\bar{t}$  events to search for LFV signals
- SM Lagrangian extended by dimension-6 operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots,$$

- 3 types of LFV interactions are considered:
- Production and decay modes



Vector	}	$O_{lq}^{(3)ijkl}$	$= (\bar{l}_i \gamma^\mu \tau^I l_j) (\bar{q}_k \gamma^\mu \tau^I q_l),$
		$O_{lq}^{(1)ijkl}$	$= (\bar{l}_i \gamma^\mu l_j) (\bar{q}_k \gamma^\mu q_l),$
		$O_{lu}^{ijkl}$	$= (\bar{l}_i \gamma^\mu l_j) (\bar{u}_k \gamma^\mu u_l),$
		$O_{eq}^{ijkl}$	$= (\bar{e}_i \gamma^\mu e_j) (\bar{q}_k \gamma^\mu q_l),$
		$O_{eu}^{ijkl}$	$= (\bar{e}_i \gamma^\mu e_j) (\bar{u}_k \gamma^\mu u_l),$
Scalar	}	$O_{lequ}^{(1)ijkl}$	$= (\bar{l}_i e_j) \varepsilon (\bar{q}_k u_l),$
		$O_{lequ}^{(3)ijkl}$	$= (\bar{l}_i \sigma^{\mu\nu} e_j) \varepsilon (\bar{q}_k \sigma_{\mu\nu} u_l),$

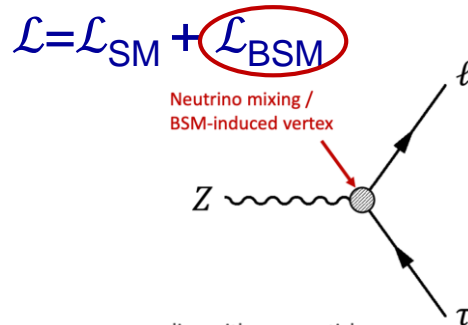
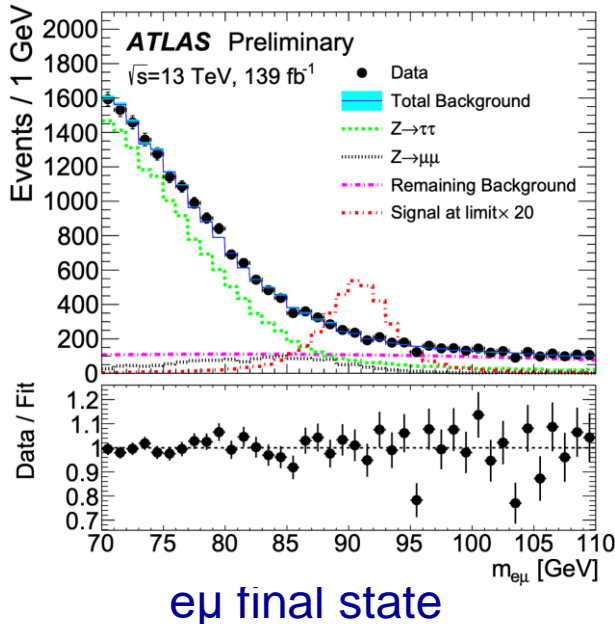


Data consistent with SM expectations

# Lepton Flavor Violation in Z boson decay ATLAS-CONF-2021-042

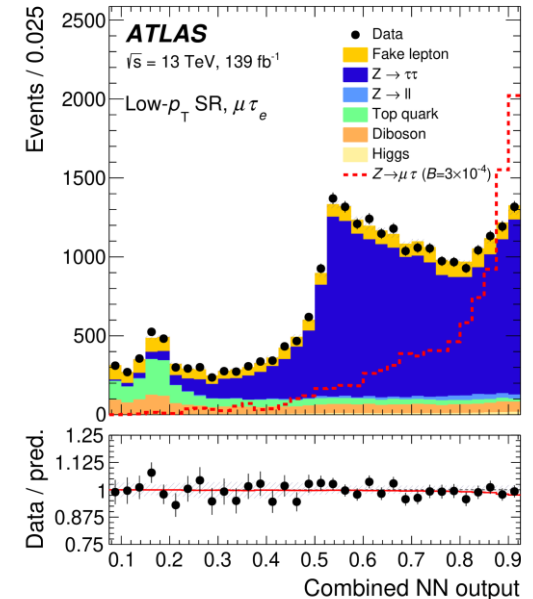


- Lepton flavor violation only observed in neutrino oscillations, ~negligible for charged leptons in SM
- Use  $\sim 8 \times 10^9$  Z bosons produced in LHC Run2
  - $Z \rightarrow e\mu$  search based on  $m_{ll}$ , w/ reduced uncert. normalizing to  $Z \rightarrow ee, \mu\mu$
  - $Z \rightarrow e\tau, \mu\tau$  search w/ NNs to suppress  $Z \rightarrow \tau\tau, tt, VV$  &  $W \rightarrow \ell\nu + \text{jets}$  bkg



Upper limits at 95% CL	ATLAS	LEP
$B(Z \rightarrow e \mu)$	$0.34 \times 10^{-6}$	$1.7 \times 10^{-6}$ (OPAL)
$B(Z \rightarrow e \tau)$	$5.0 \times 10^{-6}$	$9.8 \times 10^{-6}$ (OPAL)
$B(Z \rightarrow \mu \tau)$	$6.5 \times 10^{-6}$	$12 \times 10^{-6}$ (DELPHI)

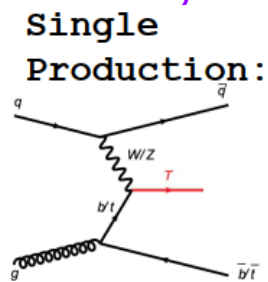
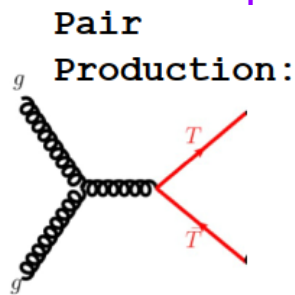
Run1+Run2



- ATLAS results improves LFV limits by a factor 5 ( $Z \rightarrow e\mu$ ) and 2 ( $Z \rightarrow e\tau, \mu\tau$ ) ([arXiv:2010.02566](https://arxiv.org/abs/2010.02566), [arXiv:2105.12491](https://arxiv.org/abs/2105.12491))

# Searches for Vector-Like Quarks (VLQ)

- Vector-like quarks (VLQ) are an important signature in many BSM models.
- Colored spin-1/2 fermions but their L/R-handed components transform the same way under gauge transformations
  - Can be “partners” to SM quarks with the same charges (e.g.  $T^{2/3}$ ,  $B^{-1/3}$ ) or can have more exotic charges ( $X^{5/3}$ ,  $Y^{-4/3}$  ...)
  - In simplified models VLQ mix with their SM partners to regulate the Higgs boson mass. mix predominately with 3<sup>rd</sup> gen. SM partners



$$T \rightarrow Wb \quad Br \sim 0.5$$

$$T \rightarrow Ht \quad Br \sim 0.25$$

$$T \rightarrow Zt \quad Br \sim 0.25$$

$$B \rightarrow Wt \quad Br \sim 0.5$$

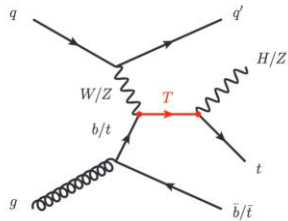
$$B \rightarrow Hb \quad Br \sim 0.25$$

$$B \rightarrow Zb \quad Br \sim 0.25$$

- Broad search program with ATLAS and CMS using full Run 2 data
- Exploit new techniques in all-hadronic (boosted) object tagging, event classification of multi-lepton final states, and more.

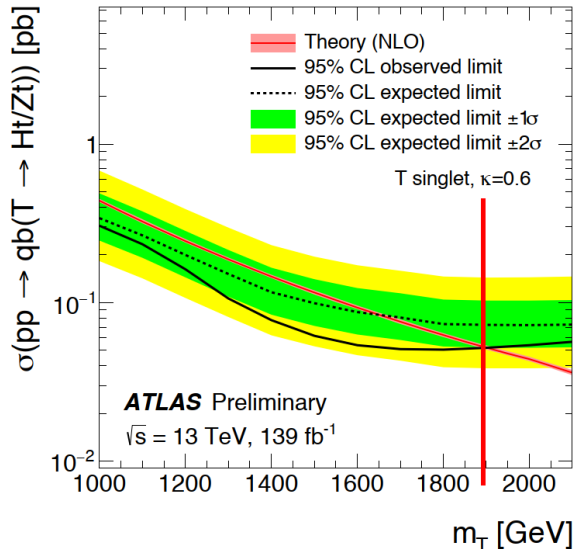
# Search for VL T and B production

## Single Production VLQ $\rightarrow$ Ht/Zt + X



ATLAS-CONF-2021-040  
 $H \rightarrow bb, Z \rightarrow qq$

- Focus on *b-associated* single Production of VL T
- High *b-tagged* multiplicity targets  $H \rightarrow bb$
- top/H/W/Z tagged with large-R jets

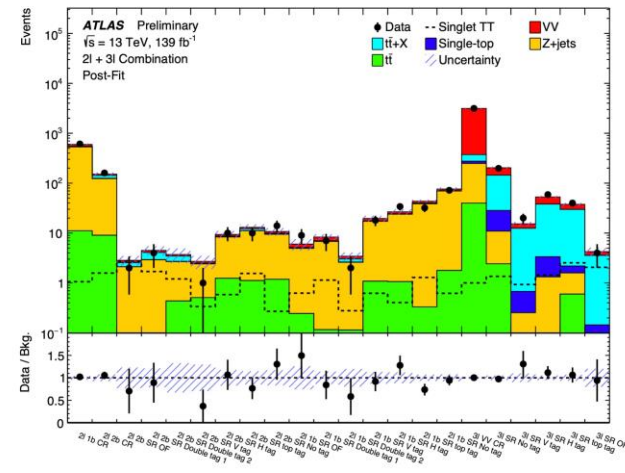
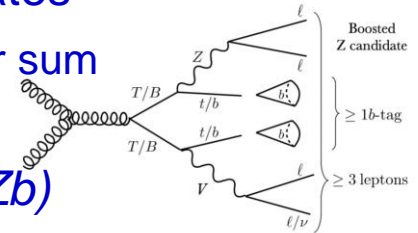


- Masses above 1.9TeV excluded for  $\kappa > 0.6$

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## Search for VL T and B Pair Production

- Focus on same flavor, opposite sign multi-lepton final states
- 3-leptons: Use scalar sum of jets & leptons
- Di-leptons: Use  $M(Zb)$
- top/Higgs/W/Z backgrounds determined from multiclass DNN



Model	Observed (Expected) Mass Limits [TeV]		
	2 $\ell$	3 $\ell$	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.29)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
100% $T \rightarrow Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.57)
$B\bar{B}$ Singlet	1.14 (1.21)	1.11 (1.10)	1.20 (1.25)
$B\bar{B}$ Doublet	1.31 (1.37)	1.07 (1.04)	1.32 (1.38)
100% $B \rightarrow Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.49)

SUS

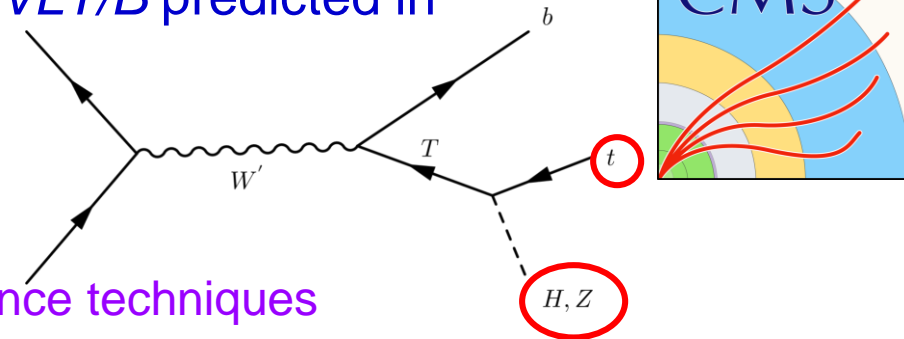
# Search for heavy $W'$ $\rightarrow$ tB or bT

• Cascade decay of heavy  $W'$  boson to VLQ/B predicted in Composite Higgs Models

• All hadronic event signature of three energetic jets (2 large R, 1 b-tagged)

• Uses variety of boosted heavy resonance techniques

• QCD multijet background predicted using transfer function in  $p_T, \eta$

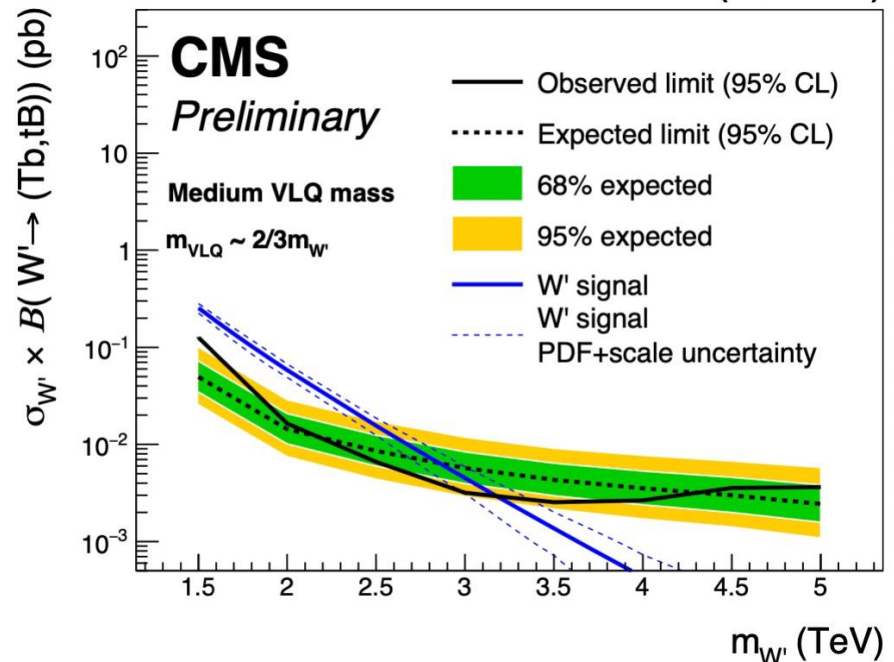


- ✓ - Benchmark point:
  - $M(\text{VLQ}) \sim 2/3 M(W')$
  - Equal tB, bT decay
  - $\text{Br}(\text{VLQ} \rightarrow Z/H) = 1/2$

✓ At benchmark point  $M(W') < 3.2 \text{ TeV}$  excluded, 95% CL

✓ Fraction  $q_T$  and  $q_B$ , and  $\text{Br}(\text{VLQ} \rightarrow Z/H)$  varied from benchmark

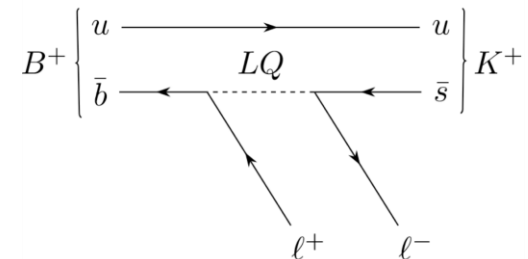
137 fb<sup>-1</sup> (13 TeV)



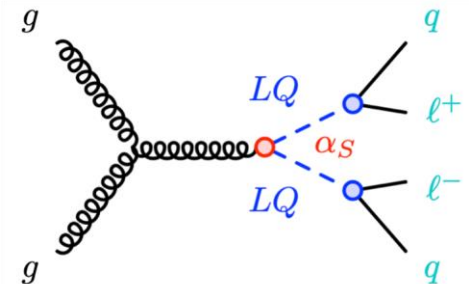


# Searches for LeptoQuarks

- LQs are hypothetical particles which mediate quark-lepton transitions, occurring naturally in models of unification or models of quark-lepton substructure
  - color-triplet bosons (spin 0 or 1) with a fractional electric charge (+2/3, -1/3 for Up or Down types)
  - could explain the LFU anomalies in B meson decays mediated by charged or neutral currents, observed by Babar, Belle & LHCb
    - Models with 3<sup>rd</sup> generation LQs and cross-generational mixing are favored by the anomaly



- LQs Pair production dominant at the LHC. characterized by their Yukawa coupling to the lepton-quark  $\lambda$ , or the relative couplings  $\beta$  that control the branching fraction to  $LQ \rightarrow q/\ell$  or  $LQ \rightarrow q\nu$
- Search strategy is based on simplified signature-based searches with various  $\beta$  scenarios including diagonal and cross-generational couplings
  - events with high  $p_T$  objects in the final state including a pair of jets and a pair of leptons or a charged lepton and a neutrino ( $E_T^{miss}$ )

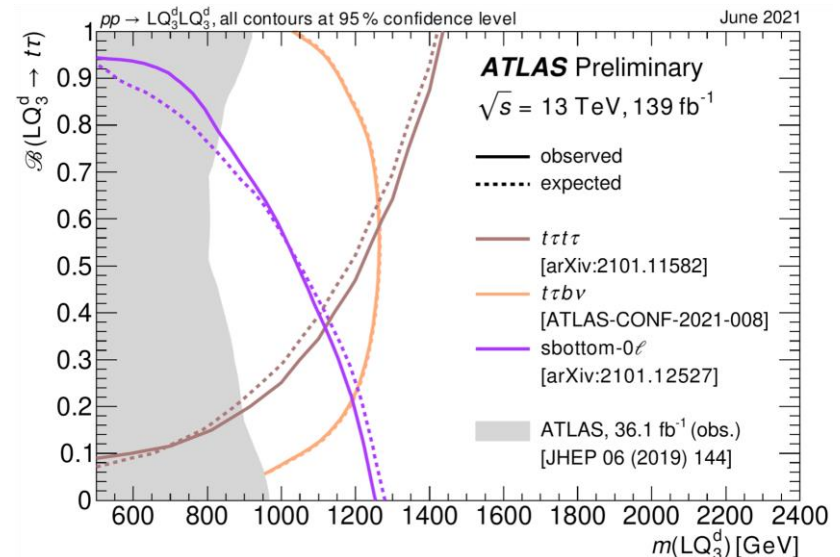
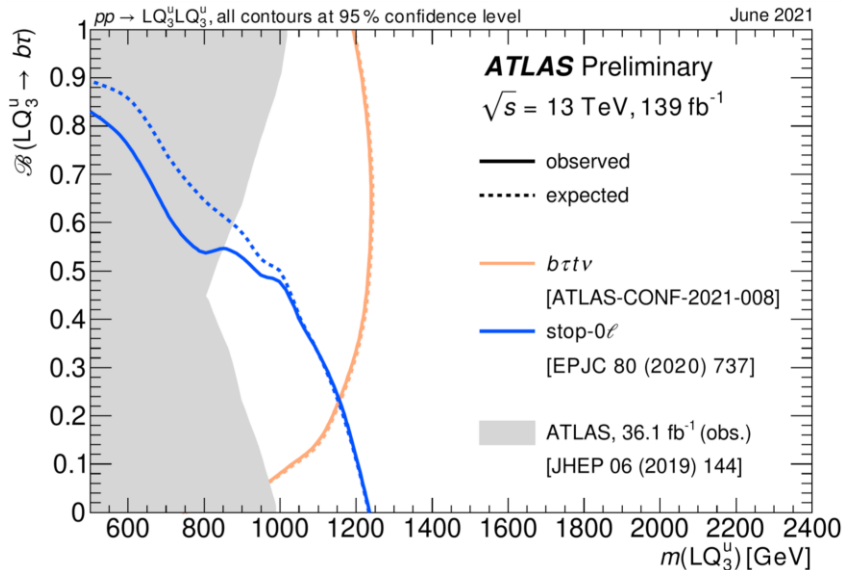


# 3<sup>rd</sup> generation scalar LQ searches (1)

- Search for down-type LQ in the  $t\tau$  decay channel (arXiv:2101.11582v1)
  - Strong limits set on mass of LQ exclusively decaying into  $t\tau$  of  $\sim 1.43$  TeV
- Reinterpretation of the search for pair-produced b-squarks decaying into  $bb + E_T^{miss}$  in terms of LQs (arXiv:2101.12527v1)
  - Limits on LQ mass are set depending on  $B(LQ_3^d \rightarrow t\tau)$  ranging from 400 GeV to 1.25 TeV
- LQ benchmark model with final states including b-jets,  $\tau$ -leptons and  $E_T^{miss}$  (ATLAS-CONF-2021-008)
  - Single- $\tau$  signal region targeting LQ search in the  $b\tau b\nu$  final state, with  $\tau \rightarrow$  hadrons
  - Analysis sensitive to both LQ types



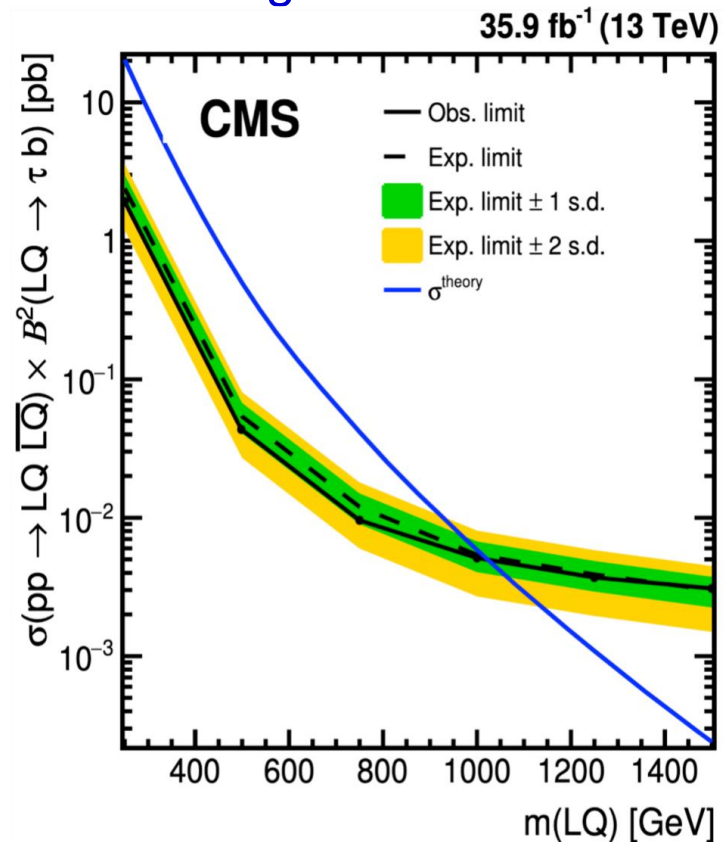
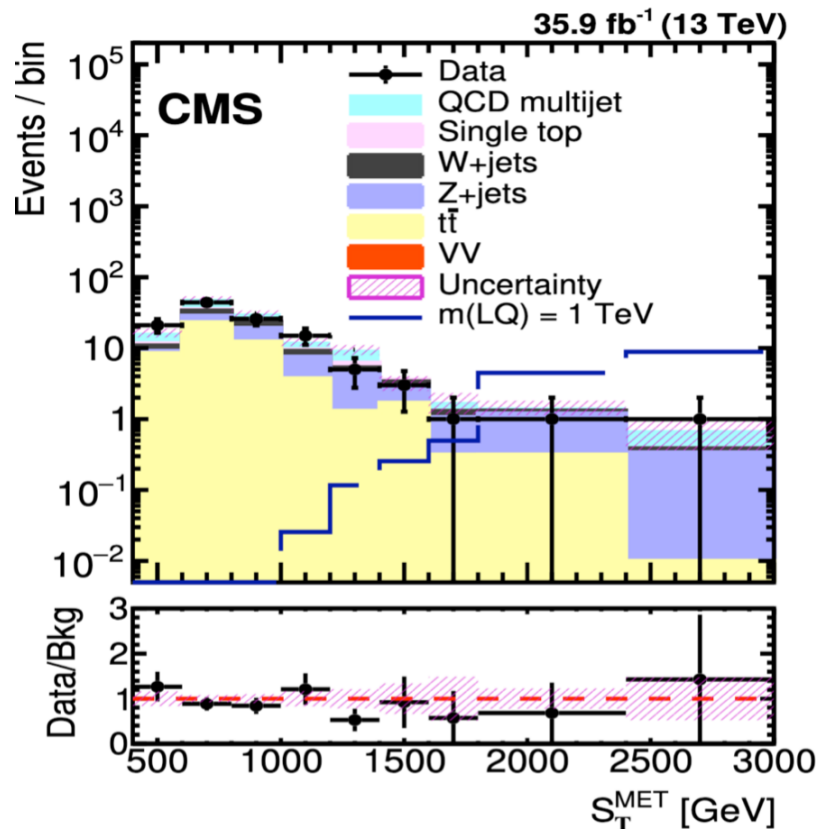
## ATLAS Summary plots



# 3<sup>rd</sup> generation scalar LQ searches (2)



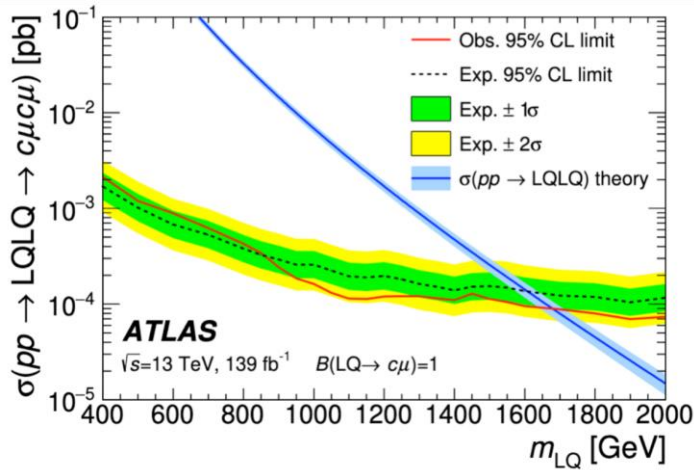
- CMS used 35.9 fb<sup>-1</sup> of data to perform a search with fully hadronic final state with two *taus* and two *non-tagged jets* (JHEP03(2019)170)
- $S_T^{MET}$  defined as the scalar sum of the  $p_T$ 's of the two hardest jets, the  $\tau$ 's and the missing  $p_T$  is used as a discriminating variable



# Search for LQ coupled to different generations (1)

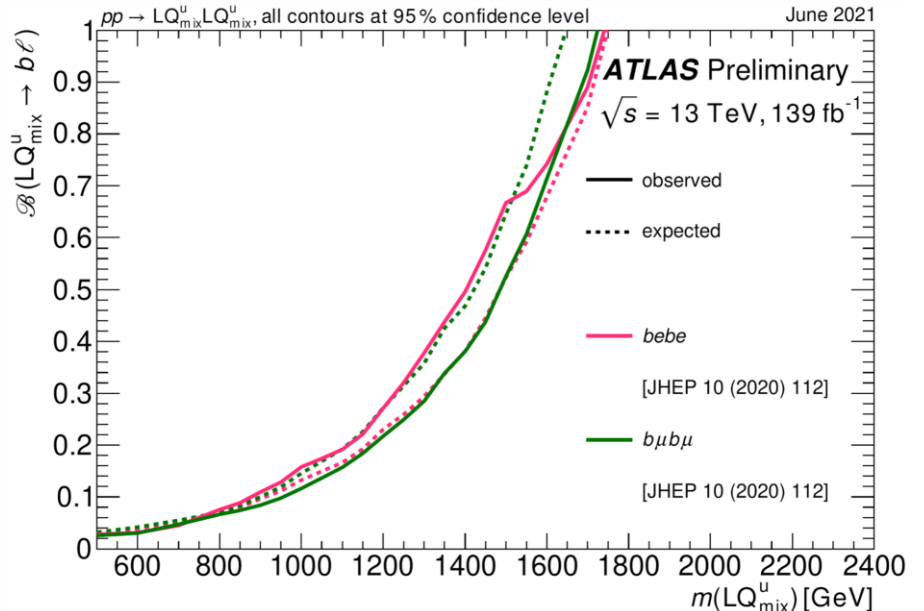
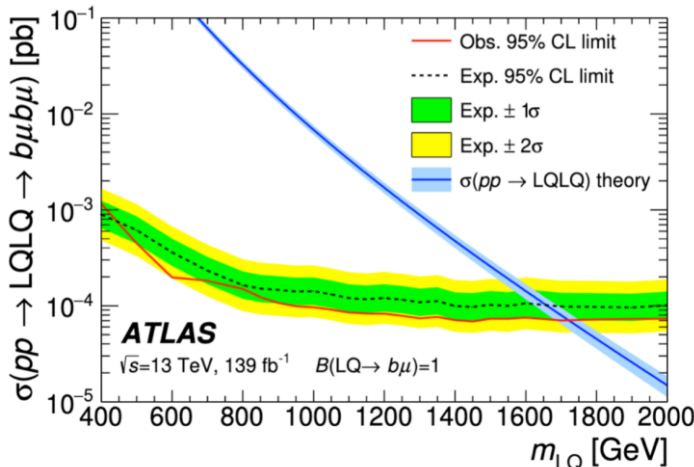


- ATLAS searched for LQs in final states from  $lQLQ$  with  $Q = c, b$ 
  - LQs that can mix quarks from different generations with  $e, \mu$
  - uses  $c$  or  $b$ -tagged jets, giving priority to  $b$ -tagging over  $c$ -tagging

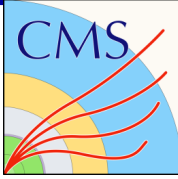


LQ masses above 1.6 TeV can be excluded in the absence of significant deviation from SM  
 JHEP10(2020)112

Limits ranging from  $\sim 500 \text{ GeV}$  to 1.6 TeV depending on the BR

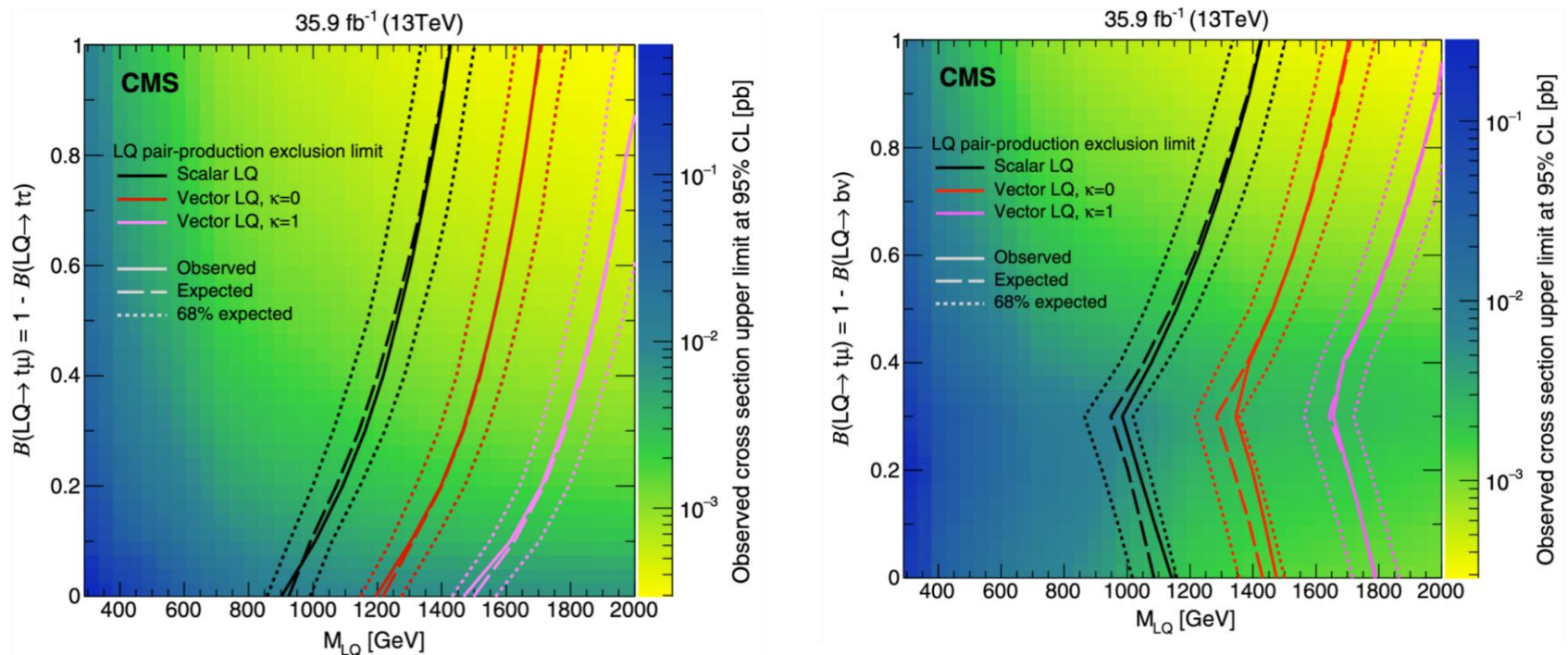


# Search for LQ coupled to different generations (2)



• CMS used  $35.9 \text{ fb}^{-1}$  of data to search for LQ decaying exclusively to  $t\mu$  using either both leptonic and hadronic  $t$ -decay

• LQs decaying exclusively to  $t\mu$  excluded up to 1420 GeV (Phys. Rev. Lett. 121 (2018) 241802)

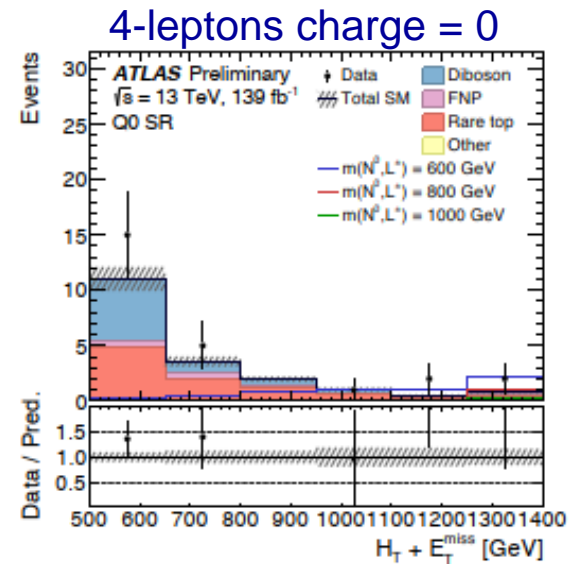
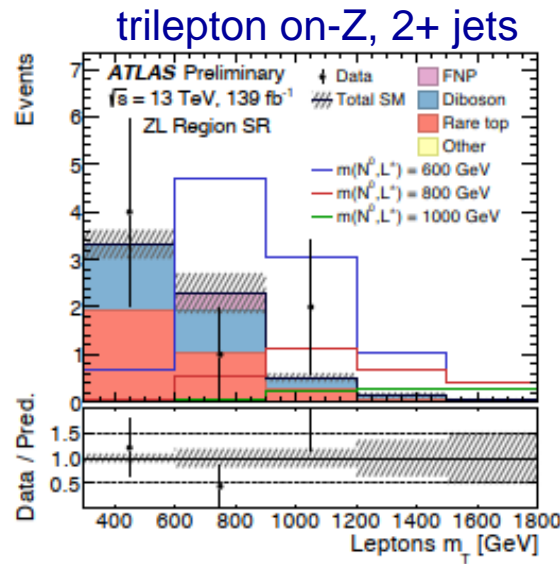
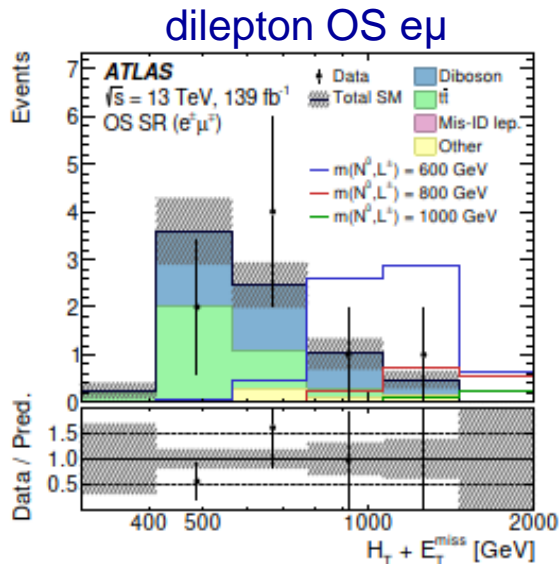
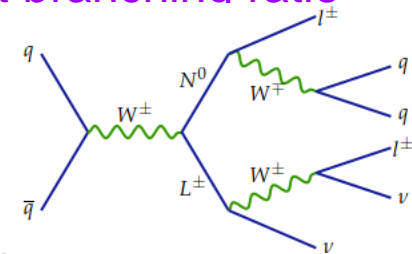


• Combination with previous results for  $t\tau$  and  $b\nu$  final states allows to set limits in two different scenarios (scalar, vector LQs)

# Other searches: Type-III Seesaw Heavy Leptons



- The seesaw mechanism: explaining the small neutrino masses
- Minimal type-III seesaw: an extra fermionic triplet: one neutral ( $N^0$ ) and two oppositely-charged leptons ( $L^+, L^-$ )
  - Decays into a SM lepton and a W, Z or H boson. W highest branching ratio
- Several leptons+jets configurations probed
  - Large fraction of background from non-prompt and fakes leptons, mis-reconstructed charge. ATLAS-CONF-2021-023
- Heavy leptons with masses below 910 GeV are excluded (*comb. 2,3,4 lep.*)



- CMS performed similar searches: ([JHEP 03 \(2020\) 051](#))

# Other searches: 4-Fermion Contact Interaction

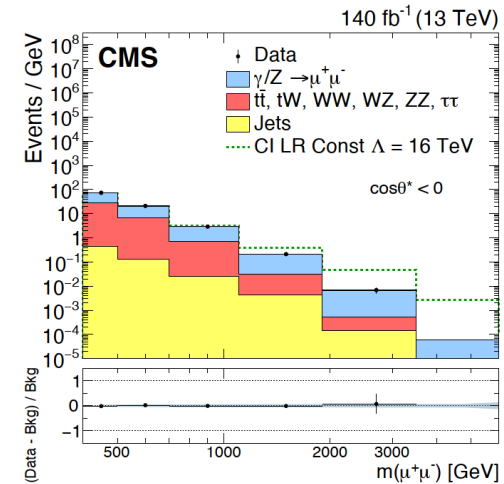
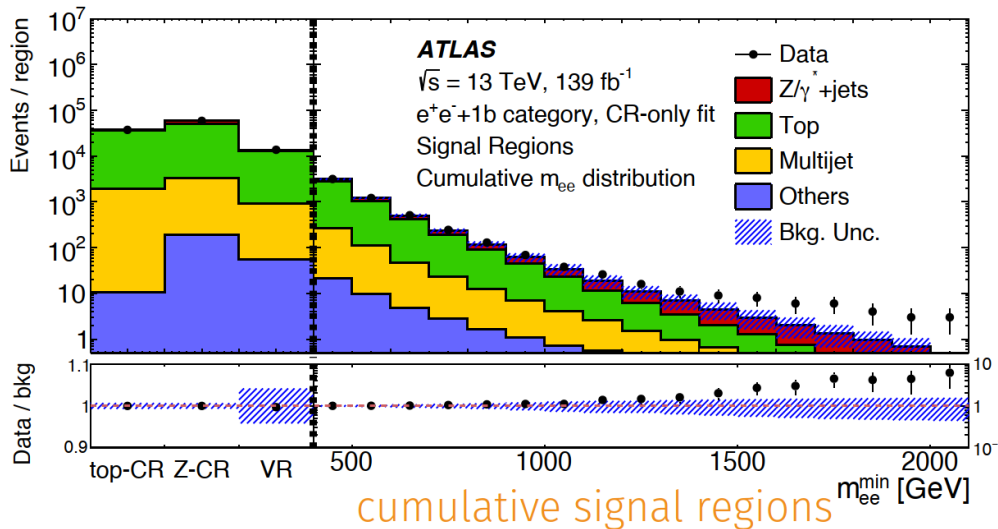
- Quarks and leptons may be composite with at least one common constituent  $\rightarrow$  effective four-fermion contact interaction at scale  $\Lambda$
- CMS studied the angle  $\theta^*$  of the outgoing negatively charged lepton with respect to the z axis in the Collins–Soper frame

$$\cos \theta^* = \frac{p_z(\ell^+ \ell^-)}{|p_z(\ell^+ \ell^-)|} \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+ \ell^-) \sqrt{m(\ell^+ \ell^-)^2 + p_T(\ell^+ \ell^-)^2}}$$

Lower limits on  $\Lambda$ : CMS: 23.9-36.4. ATLAS: 22.3-35.8

CMS-EXO-19-019, ATL-PHYS-PUB-2021-021

- ATLAS uses an EFT approach to study  $bsll$  contact interaction that could be related to flavour anomalies in



B-meson decays

different for  $e, \mu \rightarrow bsll$  contact

interaction: scale  $\Lambda$  and coupling  $g^*$

Largest observed local significance  $2.6\sigma$

Lower limits: from 1.8 to 2.4 TeV

# Conclusions

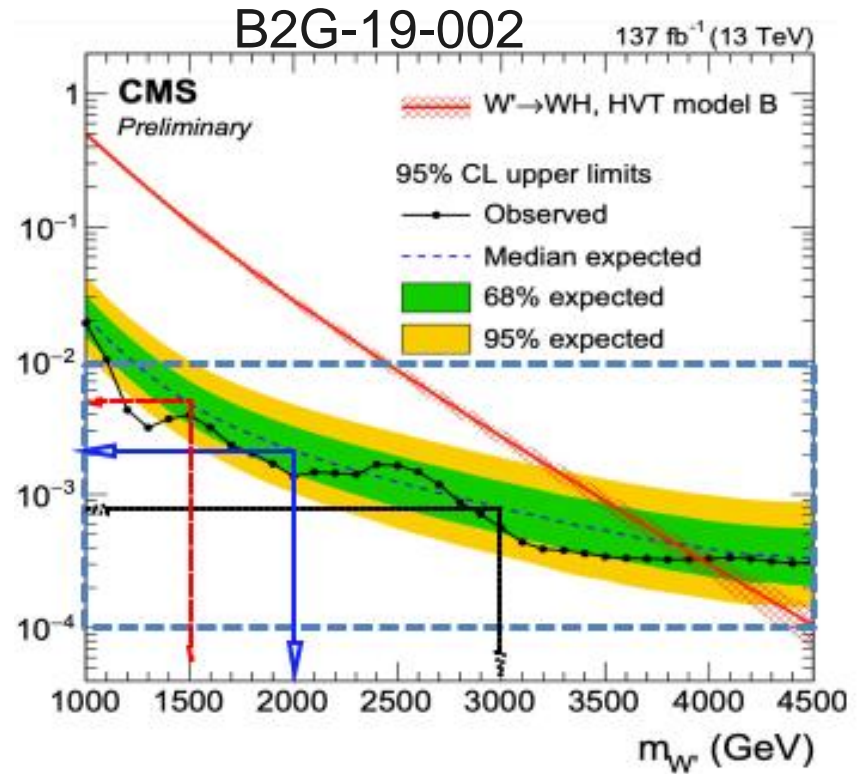
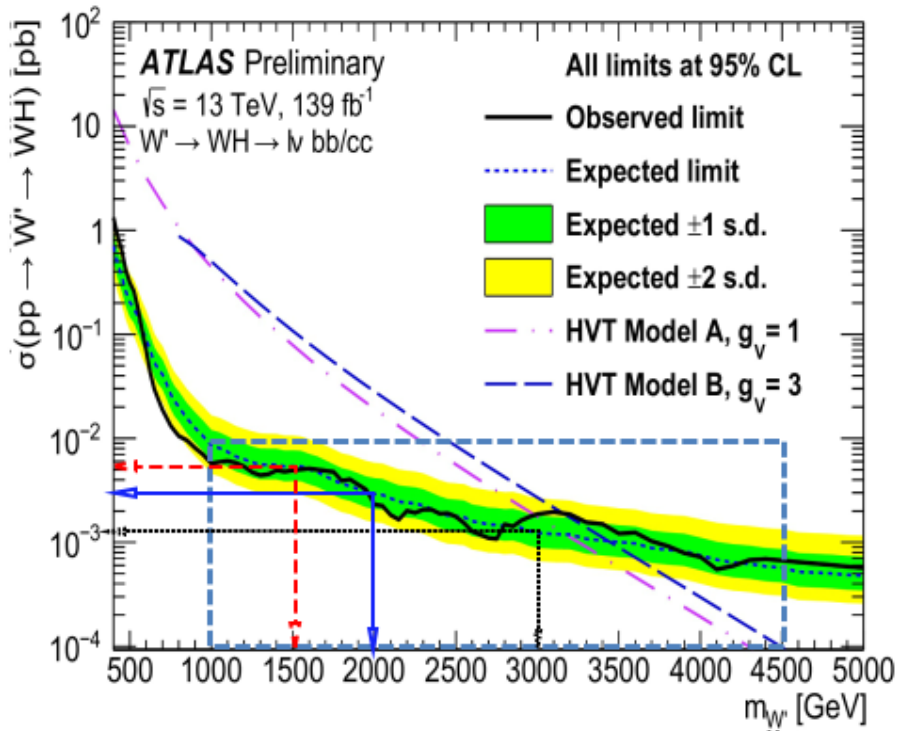
- ATLAS and CMS performed a tremendous effort to search for physics beyond the SM
  - Intense program continues to fully exploit Run 2 data
- Numerous models are being tested and their predictions cross-checked against experimental measurement
  - Heavy particles (Diboson resonances, LQ, VLQ...)
  - New interactions (FCNC, contact interaction...)
- So far, no observation of any significant differences w-r-t to SM predictions
  - Few excesses here and there are not giving a clear hint for BSM physics
- However, new approaches are continuously introduced for higher precision measurement and searches to explore hidden corner of the SM
- Run 3, with double of the current luminosity would provide even more data for more extended searches.



# Extra Material

# Diboson searches: ATLAS vs CMS results

- Both experiments searched for  $W' \rightarrow WH$  with Run2 data



- ATLAS has wider  $M_{W'}$  interpretation with 2 models
- Low masses ( $M_{W'} < 1.5 \text{ TeV}$ ) ATLAS has better limits
- High masses ( $M_{W'} > 1.5 \text{ TeV}$ ) CMS has slightly better limits